UNITED STATES

EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

PRELIMINARY REPORT

ON

RESIDUARY OR FORM RESISTANCE OF SHIPS

EXPERIMENTAL MODEL BASIN
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The form resistance of a ship is due to the inequalities of the fluid pressure distribution forward and aft while the ship is underway. If the point pressures at all parts of the bow and stern of a ship, while underway at any given speed, could be determined, the integration of these unit pressures multiplied by the projections on a transverse plane of all the elements of wetted surface would give the form resistance at that speed.

This has been done in the case of model 2861, which was made up of two equal ends each 7-1/2 feet long, and a parallel middle body 5 feet long, making a total length of 20 feet.

Fig. No. 1 shows on the body plans, contours of changes in pressure so obtained, referred to the pressure at the given point when the ship is at rest.

These results are for one particular form and in this case the bow and the stern were the same. Nevertheless, certain results of these tests are applicable to any ship and conclusions can be drawn from them which are useful in clearing up our knowledge as to how a ship's lines ought to be laid out for minimum form resistance.

Some specialized forms recently advanced, such as the Maier bow, the Yourkevitch form, even the bulbous bow and certain features of the sterns of destroyers recently experimented with, can be explained by these general considerations.

The maximum increases in pressure over the surface, in the length of the ship, occur in the region of the wave crests of the wave system alongside the ship, and the minimum pressures occur very close to the wave hollows. The pressure increase at a given section, which may be abreast such a maximum or minimum, is not, however, uniform over the entire section. The increase is a maximum in the region of the water line, and becomes generally less as the keel is approached. For our present purpose, however, it is not necessary to consider anything more than the fact that the sections showing maximum increase and decrease of pressure can be located longitudinally by the elevations or depressions of water surface in the wave contour. In other words, the crests and hollows of the wave contour indicate the parts of the ship where maxima and minima of pressure occur.

These wave contours, as far as the bow and parallel middle body are concerned, agree well with a trochoidal wave pattern of which the wave length is determined by the speed. The length of the wave in feet is very closely equal to $0.55V^2$, where V is the ship speed in knots. It is also found that the first wave crest is about 6 per cent of the wave length abaft the bow, so that the length of the first wave crest extends to a distance from the bow of about $.17V^2$. Until the

*This work is only begun, and this report is made to record the facts and preliminary conclusions.

afterbody is reached the positions of crests and hollows of the wave pattern can be found by the above considerations. In the region of the afterbody, the combined wave pattern is usually shifted somewhat ahead of where it would be except for the presence and the interference of the stern wave. This stern wave can be isolated in special model tests by introducing between the forebody and the afterbody a long length of parallel middle body as indicated in Fig. 151 of Taylor's 1933 edition of Speed and Power. The stern wave begins with a hollow at the forward end of the afterbody and may or may not have a pronounced crest abaft that.

As an example of the degree of agreement between the wave form so computed and that actually found in the case of model 2861, the following table is given, showing distances in feet from the bow:-

Model	Wave	1st	Crest	1st	Hollow	2nd	Crest	2nd	Hollow
Speed	Length	Est.	Meas.	Est.	Meas.	Est.	Meas.	Est.	Meas.
4 kts.	8.9 ft.	0.5	0.5	5.0	5.0	9.5	—	14.0	14.5
4-1/2	11.2	0.7	0.7	6.3	6.0	11.9	—	17.5	16.0
5	13.8	0.8	0.8	7.7	7.0	14.6	—	21.5	17.C

The second crest came on the parallel middle body, and its position was not measured.

We cannot expect to find in any given case by general reasoning what the actual pressure distribution will be over the bow and stern. Some theoretical work of this kind has been done, generally without any great degree of success, and model experiment must be relied on, as in the present case, to give the actual values. In the case of model 2861 these point pressures, when integrated over the underwater body, gave three points on the residuary resistance curve, one for each of the 3 speeds. The resistances so found agreed fairly closely with those determined from model resistance tests in the usual way. See Fig. 2.

The integration of these pressures is best performed by averaging on girth the pressures around each section and multiplying the average pressure thus found at each section by the projection on a transverse plane of the wetted surface between two such sections. This projection is practically the same as the area of the given portion of wetted surface multiplied by the mean slope of the surface to the fore and aft line or, what is the same thing, it is the value of the ordinate on the first derivative of the sectional area curve. This derivative is found by measuring the slopes along the sectional area curve.

The first attempts at this Basin to modify the hull form for least form resistance in connection with the pressure variations were based on this derivative curve. Where the pressure variation is unfavorable, for instance where the pressure is high in the forebody or low in the afterbody, the ordinates of the sectional area derivative curve were reduced and vice versa. In other words, the changes of sectional area from point to point were lessened wherever the pressure is unfavorable and increased wherever it is favorable. A model along these lines was tested by Taylor for the GEORGIA class, but without success.

Following out this idea, the reason for the usefulness of the Maier bow will be shown. At low speeds in a full form where the form resistance is large, most of this resistance is due to the first wave crest at the bow which causes a large increase in pressure over a short part of the length forward. The speed being low, there will be a number of wave crests and hollows along the length and the ones following the first crest will partly neutralize each other. Therefore, the first crest is the one that needs to be chiefly considered. It is obvious that for the length of this crest, which extends over about a third of the wave length from the bow, the ordinates of the sectional area <u>derivative curve</u> must be kept as small as possible. The maximum pressure is at about 6 per cent of the wave length from the bow, and at this point especially the reduction of the ordinate is necessary. This is obtained by making the ordinate of the derivative curve at the extreme bow zero. In other words, the tangent of the sectional area curve at this point is zero. Abaft this point the ordinates are kept as small as possible for the quarter length of the wave, but they must of course be soon increased to meet the rest of the curve, and this curve must have a definite area to correspond with the displacement. Over the region of the first hollow the ordinates can be increased. The reduction in resistance will be due partly to the reduction in the slope of the area curve at the extreme bow, partly to the reduction in height of the wave crest; it is obvious though that this process lengthens and modifies the crest, and much improvement cannot be expected.

Somewhat similar reasoning will show the cause of the peculiar shape of the bow lines in the case of the Yourkevitch form. This is of advantage, so far as form resistance is concerned, in any case where the first bow crest does not much exceed 1/4 or 1/3 of the length of the ship; that is, where the relative speed is not very high.

These considerations will also show why it is not necessary, or in fact desirable, to fine the ends of a very fast ship, for instance a destroyer. Here the first wave crest may cover the entire length of the ship. At 40 knots, the wave length is 900 ft. and the ship only a little over 300 ft., therefore, the ship will be nearly entirely supported on the first bow crest, which is about 270 ft. long. To obtain the least form resistance all of this part should be fined but it is of course impossible to fine any one part of the ship in preference to any other. The most that can be done is to extend this fining for as large a part of the length as possible, in other words, to make the forebody as long as possible; and, in general, it is found that a smaller resistance in a destroyer is obtained when the forebody is longer than 1/2 the length.

Certain other features can be traced on these diagrams, such as the fact that although the maximum pressures are obtained near the extreme bow, they are obtained only in the region of the water line, and the increased pressures at the forefoot are not very far from zero. The forefoot can then be made a large cylindrical body with a hemispherical end, without any appreciable increase in the form resistance. In theory, if the bulbous bow is given a hemispherical end, the net increase of pressure on this hemispherical end is not very far from zero. A bulb can therefore be worked into such a ship and provide displacement without much increase in form resistance, and it helps to fine the part of the forebody where fining is needed, at the water line.

The fact should be noted that the maximum increases in pressure are near the water line. The minimum pressures in the case of the wave hollow are also near the water line. In the case of the minima, the differences between the water line and points further down are not so great, but in the case of the maxima opposite a wave crest, the differences may be very large. The indication here is that after the most favorable sectional area curve has been determined, some attention should be given to the shape of the sections, especially where the wave crests are concerned. The water line regions should be fined where an adverse wave crest occurs to the extent that the half-breadths over the given region should not be varied to excessive extent. In other words, the projection of the area on a transverse plane should, in the region of the waterline, be kept small.

It is more difficult to see what changes should be made in the afterbody of a vessel as the wave profiles are not so readily determined. The stern wave usually shifts the position of any resultant wave crest or hollow on the afterbody from what it would be if there were a bow wave only, and in some cases neutralizes the wave, but in vessels like destroyers where the whole ship rides on less than one wave, it is not so difficult.

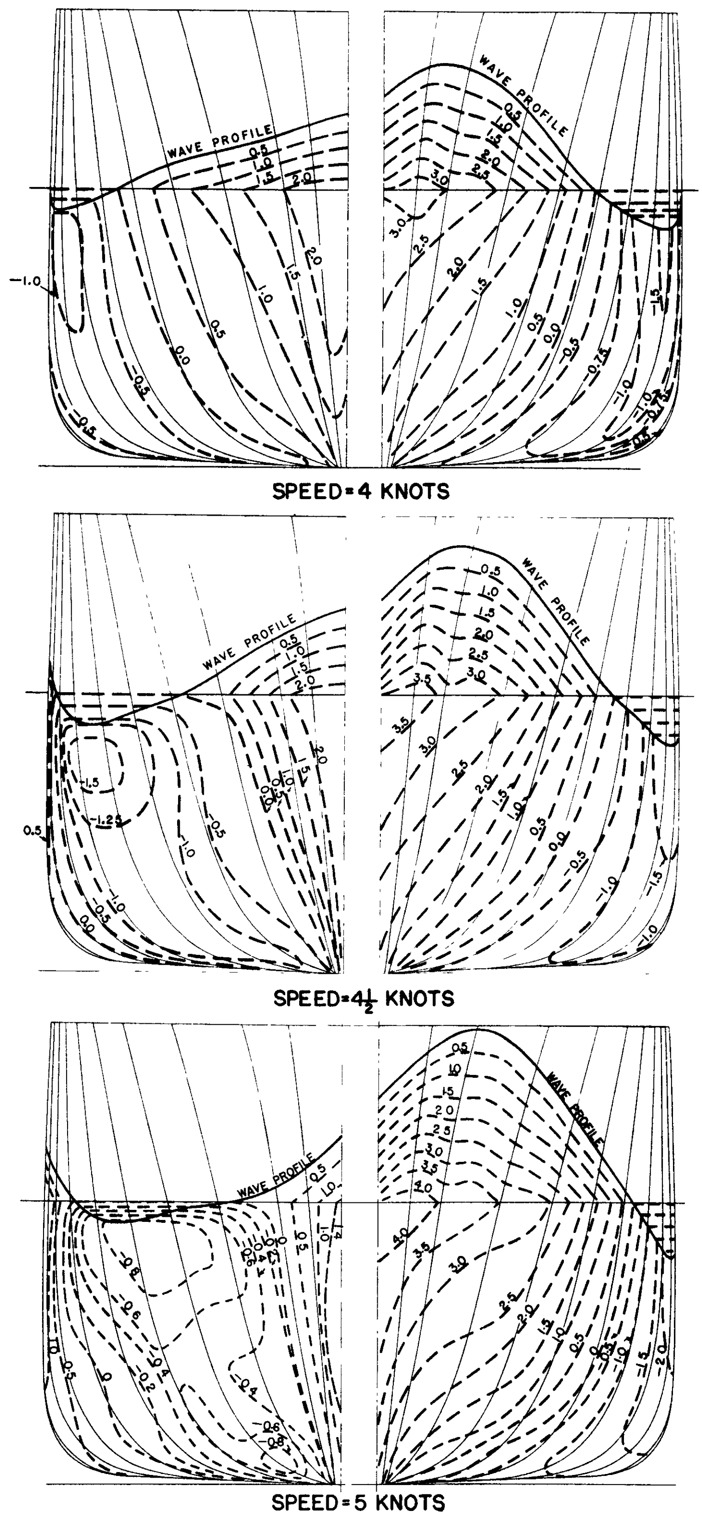
Although any reduction of resistance in the bow of the ship is always useful, a reduction in the resistance of the stern by a change in lines may not materialize as a corresponding reduction in shaft horsepower, since such a change may affect adversely the working of the propellers. Generally speaking, however, such reductions in resistance as are possible are always beneficial.

As an example of the course of reasoning that would be used to improve the lines of a ship, we may take the case of a destroyer of 334 feet at 36-1/2 knots. In this case the wave length is 740 feet, the quarter wave length is 185 feet, and 6 per cent of the length is 45 feet. Therefore, the first wave crest may be expected at 45 feet abaft the bow, and the end of this crest at 230 feet, leaving only about 100 feet of the afterbody within the region of the first hollow. As far as resistance only is concerned the first conclusion is that the forebody should extend nearly over the first 230 feet, but practically other considerations cut this length down to 200 feet or even somewhat less.

The top of the first wave crest is not reached until 45 feet of the length is passed and at the extreme bow the pressure increase is not as great as the maximum. The slopes of the sectional area curve over the extreme end can then be somewhat greater than they would be in the region of the crest. In other words, the extreme bow may be somewhat fuller than ordinarily, especially at the forefoot. However, the water line throughout the length of the bow should be as fine as possible.

Over the last 100 feet of the ship in the region of the stern where a wave hollow exists, the slopes of the sectional area curve must be kept as small as possible especially as the extreme stern is approached, where the maximum pressure differences are found. This is the same thing as saying that the sections should be kept a large fraction of the maximum. A transom of large area is of value, since the truncated part of the ship would have unfavorable pressure distribution, as well as frictional resistance. This is partly offset by the zero pressure on the transom.

It should not be inferred that the form of least residuary resistance can at once be laid down, according to the above principles, in any given case. Unfortunately, when the lines are changed, the wave contour changes also, and the final result must be guided to a large extent by an intelligent guess as to the interaction of the factors involved. Much further experimental work along these lines is necessary, before results can be obtained with certainty. The above work can be considered as a preliminary only.



BODY PLANS OF MODEL NO 2861 SHOWING

CONTOURS OF CHANGE OF PRESSURE

OCCURRING AT CERTAIN SPEEDS

PRESSURES ARE EXPRESSED IN INCHES OF WATER
POSITIVE VALUES INDICATE AN INCREASE IN PRESSURE ABOVE THAT EXISTING IN THE STATIC CONDITION
LENGTH OF MODEL = 20 FT. LENGTH OF EACH END = $7\frac{1}{2}$ FT.
LENGTH OF PARALLEL MIDDLE BODY = 5 FT.
DISTANCE BETWEEN (WHOLE) STATIONS = 0·75 FT.

Fig. 1

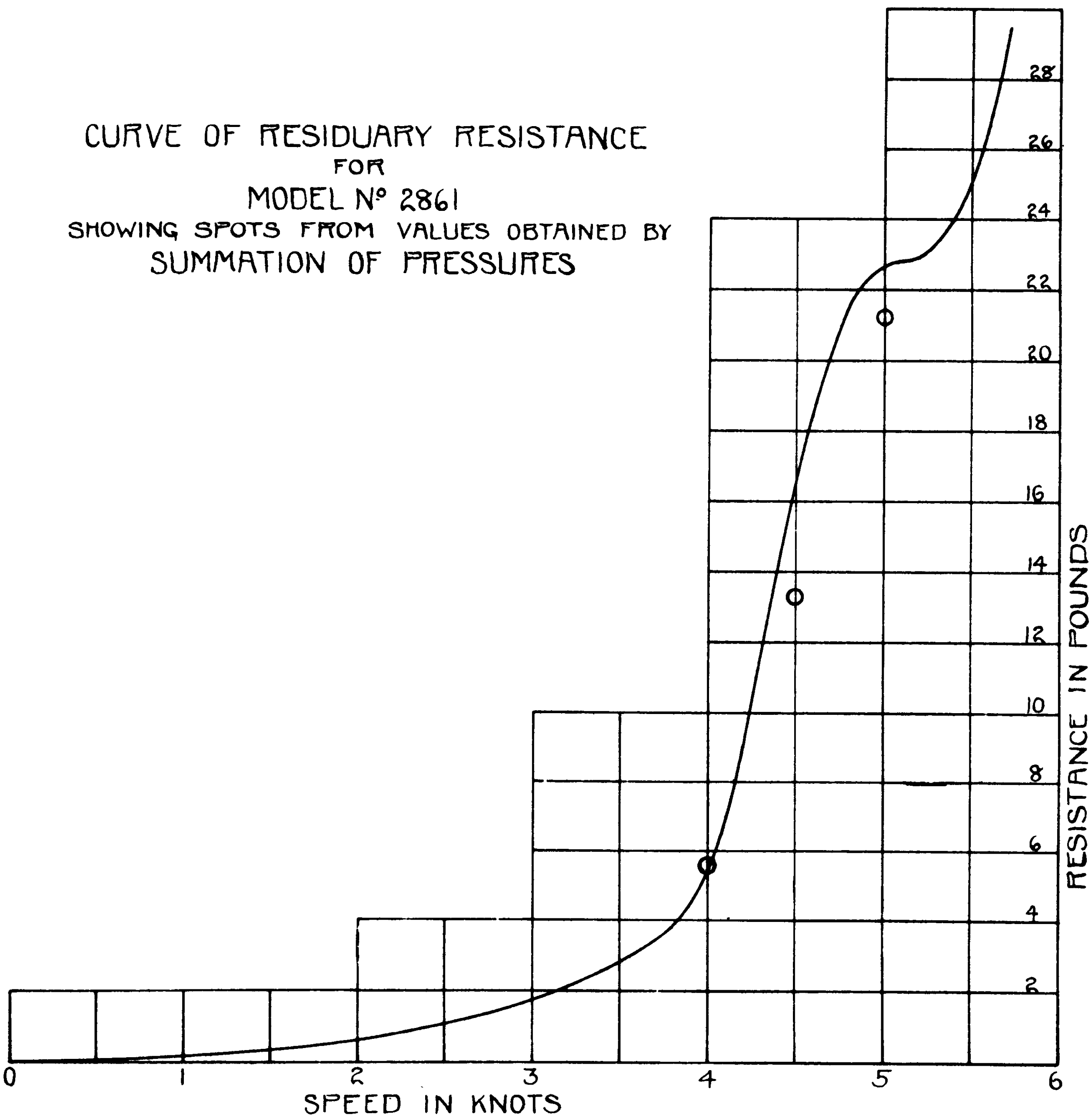

CURVE OF RESIDUARY RESISTANCE
FOR
MODEL Nº 2861
SHOWING SPOTS FROM VALUES OBTAINED BY
SUMMATION OF PRESSURES
0
1
2
3
4
5
6
SPEED IN KNOTS
2
4
6
8
10
12
14
16
18
20
22
24
26
28
RESISTANCE IN POUNDS

Fig. 2